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November 20, 2015

Dr. Robert Headrick
ONR Code: 332
Office of Naval Research
875 North Randolph Street
Arlington, VA 22203-1995

Dear Dr. Headrick,

Attached please find the progress report for ONR Contract N00014-14-C-0230 for the period of July 20, 2015 to October 19, 2015.

James C. Preisig
President, JPAnalytics LLC

CC: DCMA Boston
DTIC
Director, NRL

Report Documentation Page

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14. ABSTRACT

Description: Technical work this period has spanned three areas. The first of these is VHF Acoustics. During this time period, the Principle Investigator prepared for and conducted a VHF acoustics test in a wave tank at the Scripps Institution of Oceanography. The work, conducted in collaboration with and with the support of Dr. Grant Deane at the Scripps Institution of Oceanography yielded a rich data set characterizing the scattering of VHF acoustic signals from wind generated surface waves. The data has been quality checked and the first of the data has been analyzed. Results are described in the Major Accomplishments and Results and Recommendations sections of this report. This work falls under Research Task 2 from Section 2.2 of the Technical Approach and Justification. The first public presentation of these results will be at the 170th meeting of the Acoustical Society of America in Jacksonville, FL in November 2015. In parallel, the Principle Investigator continues to work with vendors to develop a new field deployable system for collecting VHF acoustic data in a wide range of environments.

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Progress Report #6

Coupled Research in Ocean Acoustics and Signal Processing for the Next Generation of Underwater Acoustic Communication Systems

Principal Investigator's Name:	Dr. James Preisig
Period Covered By Report:	7/20/2015 to 10/19/2015
Report Date:	11/20/2015
Contract Number:	N00014-14-C-0230
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Program Officer:	Dr. Robert Headrick ONR Code: 322 Office of Naval Research 875 North Randolph St. Arlington, VA 22203-1995 Robert.Headrick@navy.mil
Security Classification:	Unclassified
Distribution Statement:	Approved for public release. Distribution is unlimited.
Total Contract Amount:	$595,731
Costs Incurred This Period:	$45,607.75
Costs Incurred To Date:	$237,355.55
Estimated Costs To Complete:	$358,375.45

1. **Description:** Technical work this period has spanned three areas. The first of these is VHF Acoustics. During this time period, the Principle Investigator prepared for and conducted a VHF acoustics test in a wave tank at the Scripps Institution of Oceanography. The work, conducted in collaboration with and with the support of Dr. Grant Deane at the Scripps Institution of Oceanography, yielded a rich data set characterizing the scattering of VHF acoustic signals from wind generated surface waves. The data has been quality checked and the first of the data has been analyzed. Results are described in the Major Accomplishments and Results and Recommendations sections of this report. This work falls under Research Task 2 from Section 2.2 of the Technical Approach and Justification. The first public presentation of these results will be at the 170th meeting of the Acoustical Society of America in Jacksonville, FL in November 2015. In parallel, the Principle Investigator continues to work with vendors to develop a new field deployable system for collecting VHF acoustic data in a wide range of environments.

   The second area of work is that of characterizing the performance of adaptive equalizers in order to evaluate different system configuration trade-offs with respect to their impact on communications performance and ease of implementation. The Principle Investigator continued work on developing a methodology within the framework of asymptotic random matrix theory (RMT) to explicitly model the time variability of acoustic channels and using this to predict underwater acoustic communications systems performance. Specifically, current theory to date was applied to the problem of determining the optimal partitioning of a large-N array of hydrophones into subarrays for coherent processing by adaptive equalizers before combining the outputs of the subarray equalizers. Previous empirical work has shown that subarray partitioning results in both a reduction in computational complexity and improvement in equalization performance. The theory was also applied to the problem of evaluating the relative performance of linear vs decision feedback equalizers (LE vs DFE). Conventional wisdom in the underwater acoustic communications literature has been that, in order to effectively combat the intersymbol interference (ISI) caused by multipath, the best performance is provided by the DFE. However, recent empirical results using data from the KAM11 and SPACE08 experiments have shown that for multichannel equalizers utilizing large-N arrays and at low SNRs, the best performance is achieved by the LE. For both questions (Subarray Partitioning and DFE vs LE), the results of the theoretical work done this quarter back up the empirical results and are described in the Major Accomplishments and Results and Recommendations sections of this report.

This work falls under Research Task 1 from Section 2.2 of the Technical Approach and Justification of the contract proposal. The first public presentation of these results will be in a special session on Underwater Acoustic Communications at the Asilomar Conference on Signals, Systems, and Computers in November, 2015.

During this time period, the Principle Investigator also continued work with MIT/WHOI Joint Program Student, Atulya Yellepeddi, on evaluating the correlation structure of received communications signals after they have been converted to the frequency domain via Fourier Transform as described in Progress Reports #3 through #5 for the prior three reporting periods. This work falls under Research Task 3 from Section 2.2 of the Technical Approach and Justification.

2. **Major Accomplishments this Period:** The successful completion of the VHF acoustics experiment at SIO was a major accomplishment. At the VHF frequencies, the deployment of a lab computer based system is full of hidden engineering obstacles. Through a set of test deployments/experiments over the past six months, these obstacles have been identified and solutions developed. The resulting experimental data set from the latest (October 2015) experiment contains data that is rich enough to allow Drs. Preisig and Deane to begin making headway on the characterization of VHF acoustic scattering from the sea surface. Results are described in the following section.

   A second major accomplishment was the application of current RMT methods to the analysis of optimal equalizer configurations. This extends the work of *Performance Analytics and Optimal Design of Multichannel Equalizers for Underwater Acoustic Communications*. (Pajovic and Preisig) and lends new insights into the roles of subarrays and feedback filters play in adaptive equalization.

3. **Results and Recommendations:**

   The VHF acoustic wave tank experiment lent new insights into surface scattering in this regime. Due to the very short wavelength (approx. 2.7 mm at 550 kHz) very small waves (including capillary waves) have an effect on surface scattering. Noticeable effects on the scintillation index and scattering function (particularly Doppler spread) start at wind speeds of less than 2 meters/second. Very interestingly, the surface scattered signal shows an asymmetric Scattering Function with the positive Dopplers showing both a higher scattered intensity and longer delay spread. Figure 1 shows the measured channel scattering functions for wind speeds of 2 and 3.3 meters/second. The direct path arrives at the delay of approximately 10 μs while the surface scattered path arrives about 50 μs later. The color scale in this figure is 10 $\log_{10}$ the scattered field intensity One of the results of the esymmetric scattering function is that even for the case of stationary source and receiver, the surface scattered signal has a non-zero mean Doppler. Work is continuing to fully analyze the data and understand the implications of the behavior of the channel induced signal fluctuations.

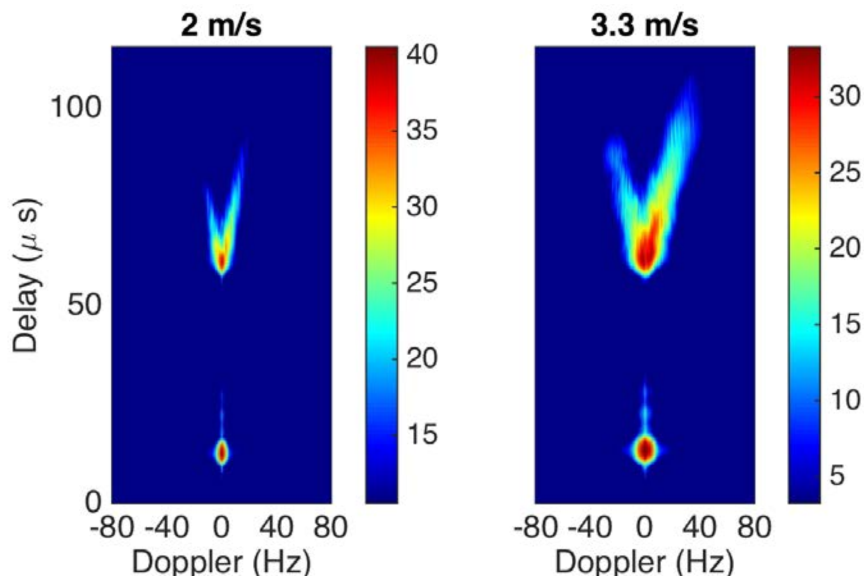

Figure 1: Measured Channel Scattering Functions

The RMT modeling of multichannel equalizer performance yielded new insights into performance trade-offs associated with subarray equalizer architectures and with DFEs and LEs. The modeled environment has a water depth of 15 meters and a source to receiver range of 3000 meters and an isovelocity sound speed profile of 1500 meters/second. The center frequency is 15 kHz, the symbol rate is 6000 symbols/second, and the full array is a vertical line array with 48 elements at a spacing of 30 cm. Figures 2 and 3 show some of the analysis results at in-band SNRs of 20 and 0 dB, respectively. In each figure, the red and blue lines correspond to the performance or equalizers with equalizer adaptation averaging intervals of 600 and 1200 symbols, respectively. Finally, in each figure the dashed line shows the performance of an LE while the solid line shows the performance of a DFE. For the DFE, the feedback filter has a length of 10 symbols. In both the LE and DFE, the feedforward filter for each array (subarray) element has 30 taps at a fractional sampling rate of 2 samples/symbol.

The data in each figure is plotted as a function of the number of array elements in each subarray. A discussion of how the elements are chosen is beyond the scope of this report. Each architecture uses the full 48 elements. For example, if there are 16 elements per subarray, then the entire array is decomposed into three subarrays. If there are 6 elements per subarray, then the entire array is decomposed into 8 subarrays. The results show three clear insights. First, as the SNR decreases, the optimal number of array elements in each subarray decreases. That is, at lower SNRs it is optimal to use smaller subarrays (more subarrays). Second, as the number observations (averaging interval for the equalizer weight adaptation process) decreases, it is optimal to use smaller subarray (more subarrays). Finally, at low SNRs (where the dominant interference is from ambient noise or interference rather than from ISI) the adaptation penalty paid for the Feedback Taps of the DFE outweights the performance improvement of using feedback taps. In this region, the LE begins to slightly outperform the DFE.

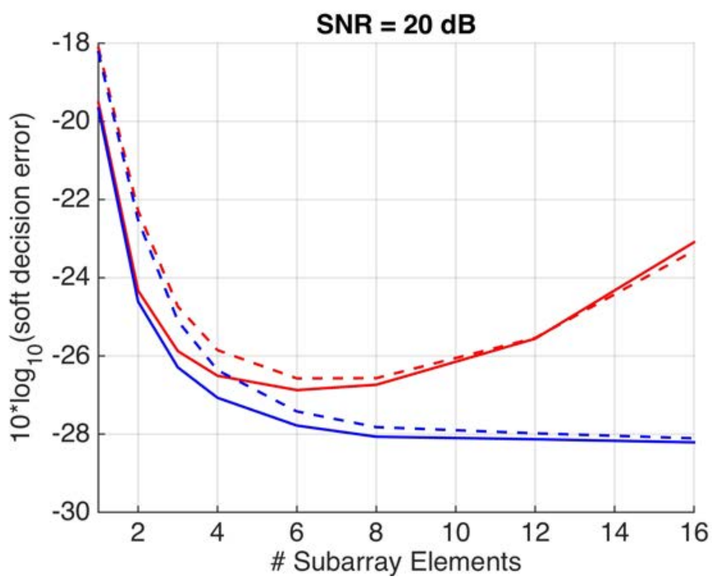

Figure 2: Equalizer Performance at 20 dB Received In-Band SNR

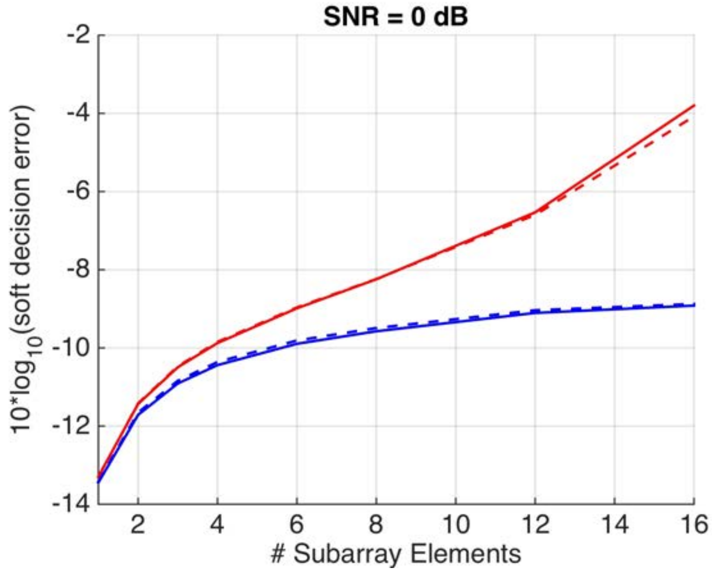

Figure 3: Equalizer Performance at 0 dB Received In-Band SNR

4. **Publications and Presentations:** None